

IMPACT OF ROAD ROUGHNESS FEATURES ON DAMAGE TO TRANSPORTED GOODS

Graduate of Polytechnic School of Tunisia, 2004. Completed a master degree in 2005 in applied math to computer science, M.S. and Ph.D. degrees in Pavement engineering from Michigan State University, USA, in 2008 and 2010. Currently she is a Research Associate at the civil and environmental engineering department at MSU.

Email: zaabarim@egr.msu.edu

Imen ZAABAR

Michigan State University
USA



Obtained B.S. and M.S. from Michigan State University, USA, in 1985 and 1987 and a Ph.D. degree in Pavement Engineering from the University of California-Berkeley in 1992. Joined the civil and environmental engineering department at MSU in 1993 where he is currently a Professor.

Email: chatti@egr.msu.edu

Karim CHATTI

Michigan State University
USA

Abstract

In this paper, we propose a novel approach to estimate the damage induced to transported goods by roughness features. The approach proposed herein uses a mechanistic-empirical approach to conduct product fragility assessment using numerical modeling of vehicle and product vibration response. A half-truck model was used to simulate vehicle vibrations. The principle of conservation of momentum (inelastic shocks) was used to estimate damage to goods. The analysis of three case studies for horticultural produce showed that: air suspensions cause less damage to the transported goods than steel suspensions; shorter spacing between faults in jointed concrete pavements will cause less damage to the transported goods in trucks with steel suspension; low speed will cause more damage to transported goods in trucks with steel suspensions than higher speed; and more breaks on the road will cause more damage to the transported goods. The approach reported in this paper could help in better estimating vehicle operating costs at the project and network levels.

Keywords: Transportation cost, Damage to goods, Roughness features.

1. Introduction

This paper presents a methodology to estimate the effect of roughness features on damage to goods. A mechanistic-empirical approach to conduct fatigue damage analysis using numerical modeling of vehicle response and product vibrations is discussed. This is followed by case studies and results from the application of the mechanistic-empirical model developed in this research.

2. Background

2.1 Pavement roughness features

Roughness features are important factors in pavement design and management. Their evaluation is an important part of the pavement management system by which a most effective strategy for maintenance and rehabilitation can be developed. Our concern in this paper is the detection of faults, breaks and curling in concrete pavements and potholes in asphalt pavements. The definitions of each of these roughness features are summarized below (Huang, 2003).

Faulting

Faulting is the difference in elevation across a joint or crack. It is determined by measuring the difference in elevation between the approach slab and the adjacent slab. In the current practice of road surface profile measurement in the US, the reporting interval for elevation is 0.025 to 0.075 m (1 to 3 inches). Based on previous study by Chatti et al (2008), for a sampling interval of 0.019 m and a reporting interval of 0.075 m, the correct height of a fault is detectable when it is calculated as the difference in elevation between points that are 0.15 m apart. Accordingly, the width of a fault was taken as this value.

Breaks

Break is a broken portion of the pavement section that starts with a negative fault and ends with a positive fault. The distance between the two opposite faults should not exceed 0.9 m (3ft), see Huang (2003).

Curling

Curling is the distortion of a slab into a curved shape by upward or downward bending of the edges. This distortion can lift the edges of the slab from the base leaving an unsupported edge or corner which can crack when heavy loads are applied. Sometimes, curling is evident at any early age. In other cases, slabs may curl over an extended period of time.

2.2 Rigid Pavement Types

Jointed plain concrete pavement (JPCP)

This is the most common type of rigid pavement. JPCP controls cracks by dividing the pavement into individual slabs separated by contraction joints. Slabs are typically between 3.7 m (12 ft.) and 6.1 m (20 ft.) long.

Jointed reinforced concrete pavement (JRCP)

JRCP slabs are much longer (as long as 15 m (50 ft.)) than JPCP slabs; so JRCP uses reinforcing steel within each slab to control cracking. This pavement type is no longer constructed in the U.S. due to some long-term performance problems.

3. Research Approach

A sensitivity analysis was performed to quantify the relationship between roughness feature height and width to damage to goods. The analysis consists of the following steps:

1. Generate road surface profile and roughness features (transient events);
2. Estimate the vehicle response and the product vibration to these transient events;
3. Compute the induced damage to transported goods;
4. Repeat all steps for different heights and frequencies of roughness features.

3.1 Artificial Generation of Profiles and Roughness Features

The pavement surface roughness profiles were generated using Equation (1) (Robson, 1979):

$$S_u(k) = c|k|^{-n} \quad (1)$$

where:

- $S_u(k)$ = displacement spectral density, $m^3/cycle$
- n = 2.5
- k = wavenumber

The constant c in Equation 1 could be estimated using Equation (2) (Hardy and Cebon, 1995)

$$c \approx 1.69 \times 10^{-8} (IRI)^2 \left(m^{1/2} cycle^{3/2} \right) \quad (2)$$

To generate a random road surface profile, a set of random phase angles uniformly distributed between 0 and 2π is applied to the desired spectral density. Then, the inverse discrete Fourier transform was applied to the spectral coefficients (Cebon, 1997).

The roughness features considered in this study are: faulting, breaks and curling in concrete pavements. To investigate their effect, these roughness features were artificially generated and superimposed on to the generated road surface profile (Zaabar and Chatti, 2010). The resulting road profile over 1.6 km is:

$$u(x) = u_r(x) + u_f(x) \quad (3)$$

where

- $u_r(x)$ = road surface profile
- $u_f(x)$ = roughness features
- $$= \begin{cases} u_{if}(x) & \frac{i*1600}{N} \leq x \leq \frac{i*1600}{N} + h; \quad i = 1:N; \quad x+h < 1600m \\ 0 & \text{Otherwise} \end{cases}$$
- N = number of roughness features per 1.6 km
- H = width of the roughness features
- $U_{if}(x)$ = roughness feature (Figure 1)

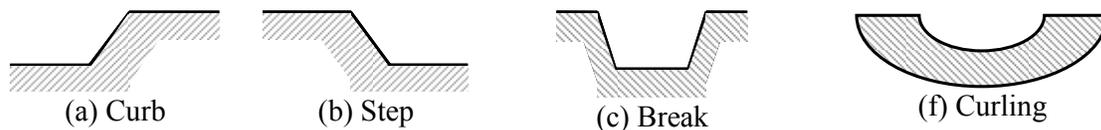


Figure 1 – Schematic description of roughness features

3.2 Dynamic Vehicle Simulation

Trucks are modeled as a two-axle vehicle. Table 1 presents the parameter values for a “standard vehicle”.

Table 1 – Unit Costs Parameter Values for a “Standard Vehicle” (Jones et al., 1991)

Name	Notation	Values	Unit
Moment of inertia about CG of body	I	31000	Kg m ²
Mass of the vehicle body	M1	5395	Kg
Distance from front axle to CG of body	R	3.5	m
Distance from rear axle to CG of body	S	1.09	m
Mass of front axle	M2	336	Kg
Mass of rear axle	M3	1000	Kg
Front spring stiffness	K1	250000	N m ⁻¹
Front spring viscous damping	C1 (bump) C1 (rebound)	1000 4000	N m ⁻¹ s ⁻¹
Front spring Coulomb damping	B1	2000	N
Rear spring stiffness	K2	1295000	N m ⁻¹
Rear spring viscous damping	C2 (bump) C2 (rebound)	4000 4000	N m ⁻¹ s ⁻¹
Rear spring Coulomb damping	B2	4000	N
Front tire stiffness	K3	1564000	N m ⁻¹
Front tire viscous damping	C3	1000	N m ⁻¹ s ⁻¹
Rear tire stiffness	K4	3078000	N m ⁻¹
Rear tire viscous damping	C4	2000	N m ⁻¹ s ⁻¹

3.3 Product Vibration

In this paper, we focused on the damage to horticultural produce. Models for horticultural produce are based on the principle of conservation of momentum (Figure 2). They treat the collision of products in multi-layered packs with the surface as inelastic shocks.

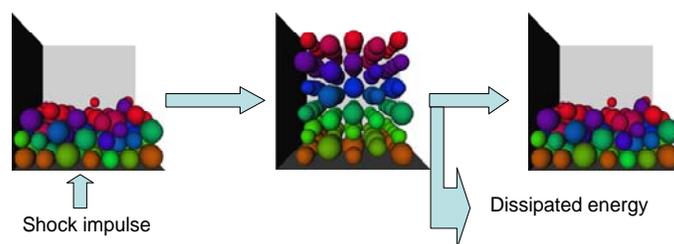


Figure 2 – Collision of horticultural produce treated as inelastic shocks

3.4 Product Damage Analysis

According to the United States Department of Agriculture Economic Research Service, apples are the most popular in the United States, and no other fruit was consumed in as large of a quantity (Rich et al, 2008; Texas Department of Agriculture, 2007). Therefore, only apples were considered in this study because including all products will be a cumbersome analysis. The kinetic energy of the falling column is dissipated by bruising of apples at the various interfaces. The first collision will be between the truck bed and the first layer of the package. The second collision will be between the second layer and the layers beneath it (Figure 3). This iterative process is repeated for all the layers. If the dissipated energy is larger than the energy resistance of the produce, damage will occur. If the percentage of the transported produce exceeds 5%, then the height and/or the width of the roughness event are not acceptable. Apples are damaged when the frequency is less than 5 Hz and the dissipated energy into the apple exceeds 6.4 ml J⁻¹ (Jones et al., 1991; Chesson et al, 1971; Timm, 1998).

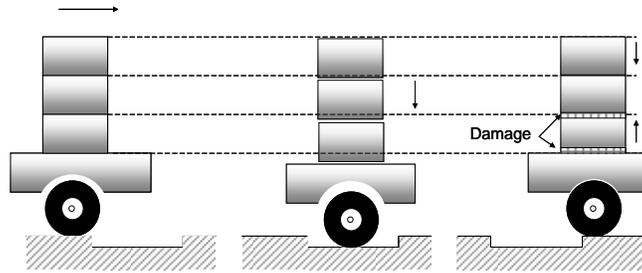


Figure 3 – Road-vehicle-load interaction for multi-layered energy absorbing packages

4. Results

4.1 Introduction

To illustrate the various features of the method described above, the case study of US conditions has been examined. All road surface profiles were artificially generated at every 0.07 m. The generated road surface profiles were filtered out using a moving average filter with a baselength of 0.3 m for trucks representing the tire enveloping. Then, the truck model traveling at a constant speed of 110 km/h was applied to a 1.6 km of road surface profiles. For all case studies, the trip length was assumed constant and equal to the typical value in the US, i.e., 2400 km (Hendrickson, 2004). The effect of different combinations of roughness features magnitude and frequency for different trip lengths of concrete pavements on damage to goods was also investigated.

Typical characteristics for trucks and packaging used to transport horticultural produce are given in Table 2.

Table 2 – Summary of truck and packaging parameter values for horticultural produce

Parameter	Values
Trailer length (m)	16
Trailer width (m)	2.6
Trailer height (m)	4
Maximum allowable GVW (metric tonnes)	45.4
Maximum allowable payload (metric tonnes)	36.2
Packaging box length (m)	0.38
Packaging box width (m)	0.32
Packaging box height (mm)	0.38
Packaging box weight (kg)	10
Number of apples per box	120
Number of boxes per trailer	3360
Packaging layout	Columns

4.2 Effect of Faulting on Damage to goods

The first case study examines the effect of different combinations of faulting levels and frequencies per 1.6 km on damage to goods. The vehicle speed was the same for all the runs. Only jointed plain concrete pavement (JPCP) were considered in this analysis since Jointed Reinforced Concrete Pavement are no longer used in the US. The effect of suspension type on

damage to goods was also investigated. Figure 4 shows the increase in percent of damaged boxes as a function of fault magnitude. It was noted that shorter spacing between faults in jointed concrete pavements will cause less damage to the goods transported in trucks with steel suspension. This observation is not true for trucks with air suspensions. It is believed that these observations were the result of the interaction between speed, profile wavelength content, resonant frequencies of trucks and goods. Figure 5 shows the effect of speed on damage to goods. It was observed:

For trucks with steel suspensions (Figure 5a)

- High speed will cause less damage to goods than low speed except for the case where all the joints in the JPCP pavements are faulted.
- The difference between pavement conditions is even greater with lower speed.

For trucks with air suspensions (Figure 5b)

- In concrete pavements where 100% of slabs are with 1 crack, high speed will cause less damage to goods than low speed.
- When all the joints in the JPCP pavements are faulted, the speed has no effect on damage to goods.

When 50% of slabs are faulted, the multiple resonant frequencies of the truck model cause the curve to oscillate.

4.3 Effect of Breaks on Damage to goods

The second case study examines the effect of different combinations of breaks/potholes levels and frequencies per 1.6 km on damage to goods. The effect of truck suspensions (i.e., air and steel) is also investigated. The breaks were modeled as a step function of variable amplitude and a length of 0.9 m. Figure 6 shows the increase in percent of damaged boxes as a function of break magnitude. As expected, more breaks in the roads will cause more damage to the cargo. Also, vehicles with air suspension cause less damage than those with steel spring suspension for apples. The difference in damage between steel and air suspensions is significant. Since the road isolation ability of air ride suspensions is higher than leaf spring suspensions, they will absorb more energy induced by the vertically accelerated wheel, allowing the frame and body to ride undisturbed while the wheels follow the bumps/depression in the road. This difference becomes less significant as the number of breaks increases.

4.4 Effect of Curling on Damage to goods

The third case study examines the effect of different combinations of curling magnitude and frequencies for 1.6 km of concrete pavements on damage to goods. Curling is modeled as an ellipsoid of variable amplitude and width. The curling width is assumed as any value between 3 m (minimum) and slab length (maximum). Figure 7 shows damage as a function of curling magnitude. As expected, higher magnitudes and more curling in the roads will cause more damage to the cargo. Vehicles with air suspension cause even less damage for apples than those with steel spring suspension as compared to breaks. The difference in damage between steel and air suspensions is very significant. This difference becomes less significant as the number of curling increases.

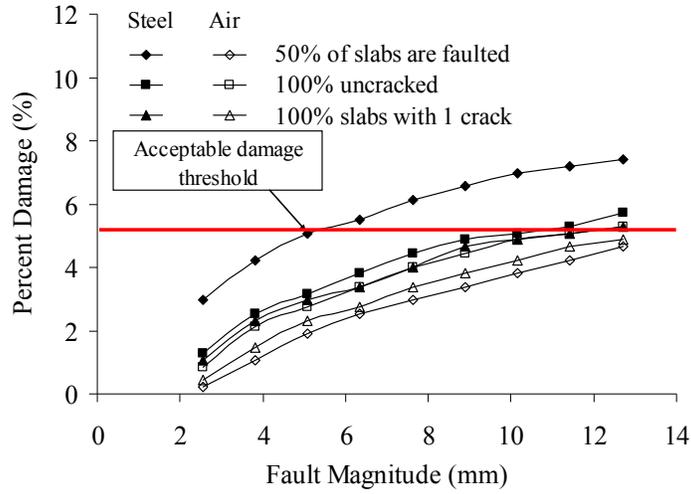
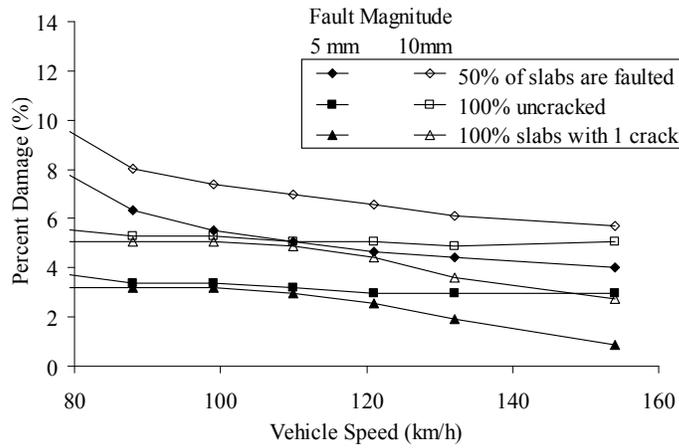
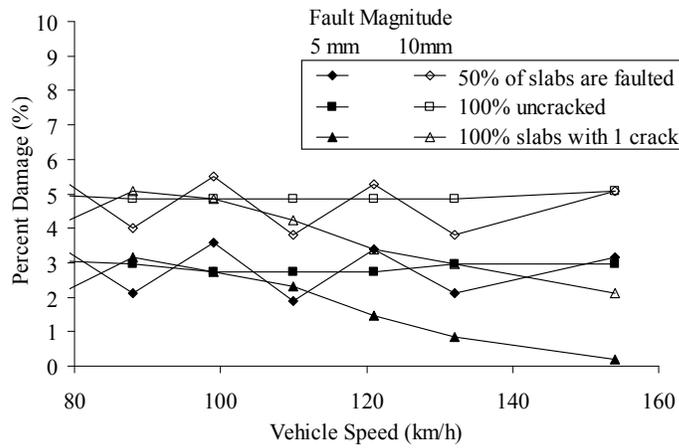


Figure 4 – Damage induced by different levels and counts of faulting



(a) Steel suspension



(b) Air suspension

Figure 5 – Interaction effect between speed and fault counts on damage to apples

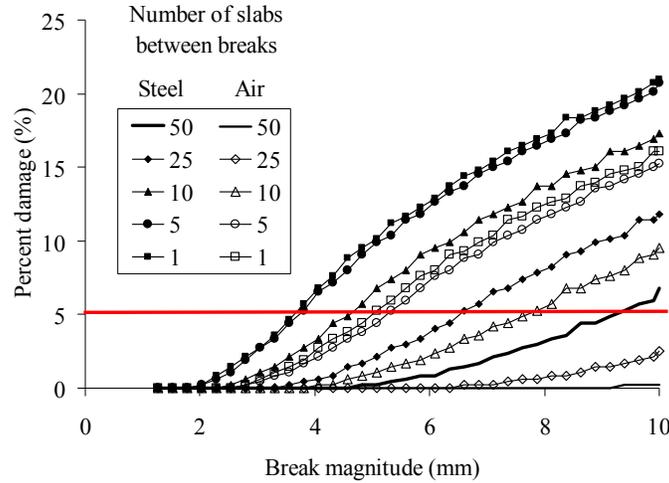


Figure 6 – Damage induced by different levels and counts of breaks

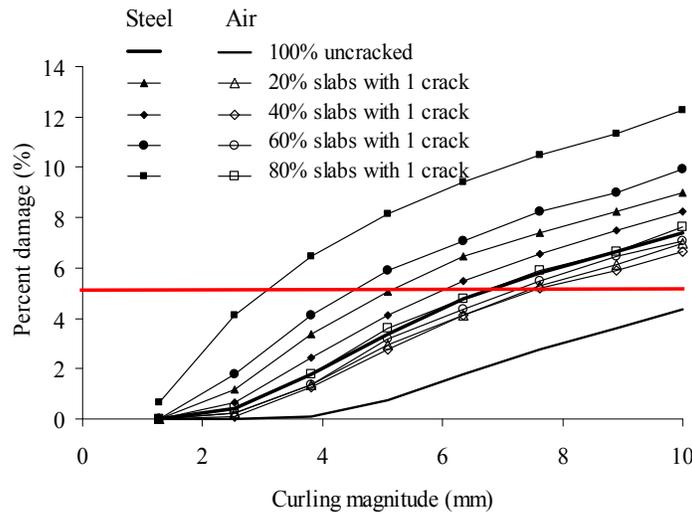
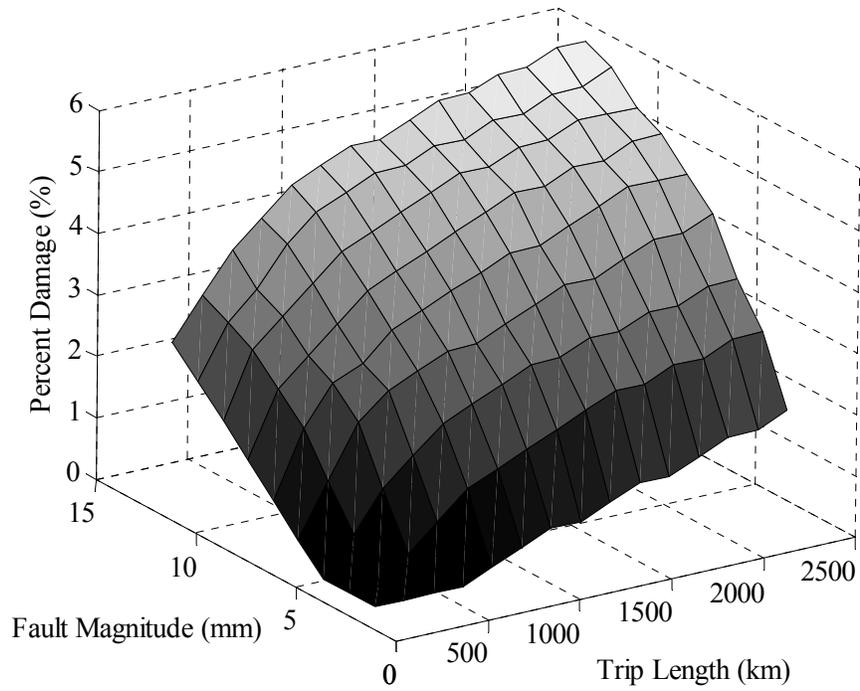


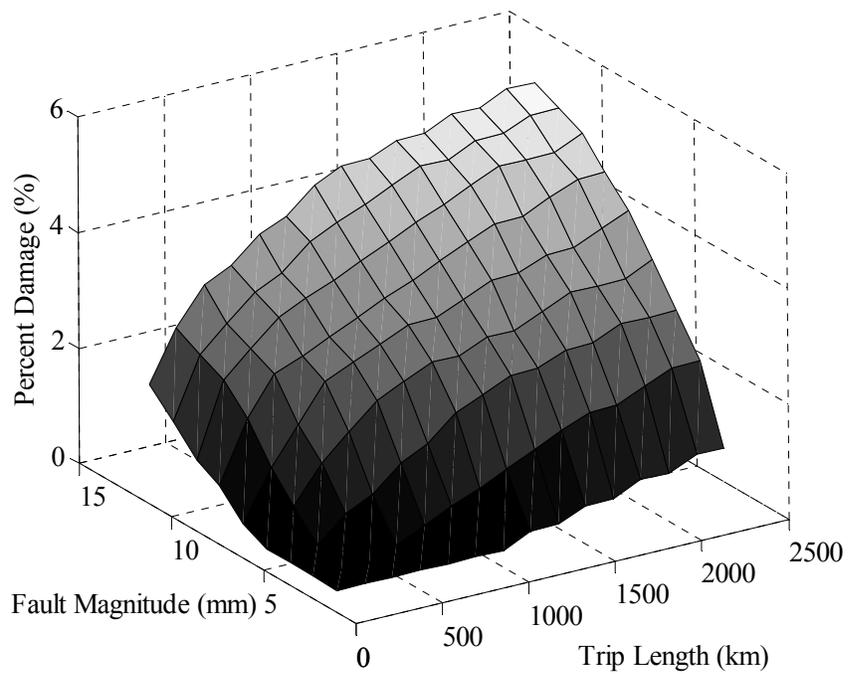
Figure 7 – Damage Induced by Different Levels and Counts of Curling

4.5 Effect of Interaction between Roughness Features Magnitude, Frequencies and Trip Length on Damage to Goods

For all previous case studies, the trip length was assumed constant and equal to the typical value in the US, i.e., 2400 km. However, trip length ranges from 160 km (local trip) to 2400 km (Shipping from California). The fourth case study examines the effect of different combinations of roughness features magnitude and frequency for different trip lengths of concrete pavements on damage to goods. Figures 8 and 9 shows the results for faulting and breaks.

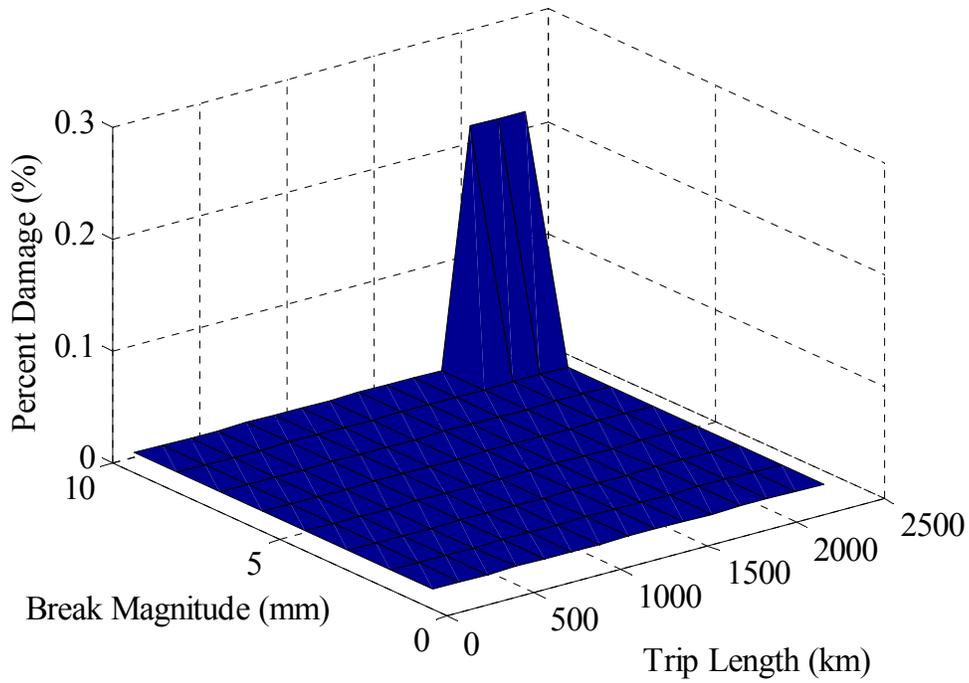


(a) 50 % of slabs are faulted

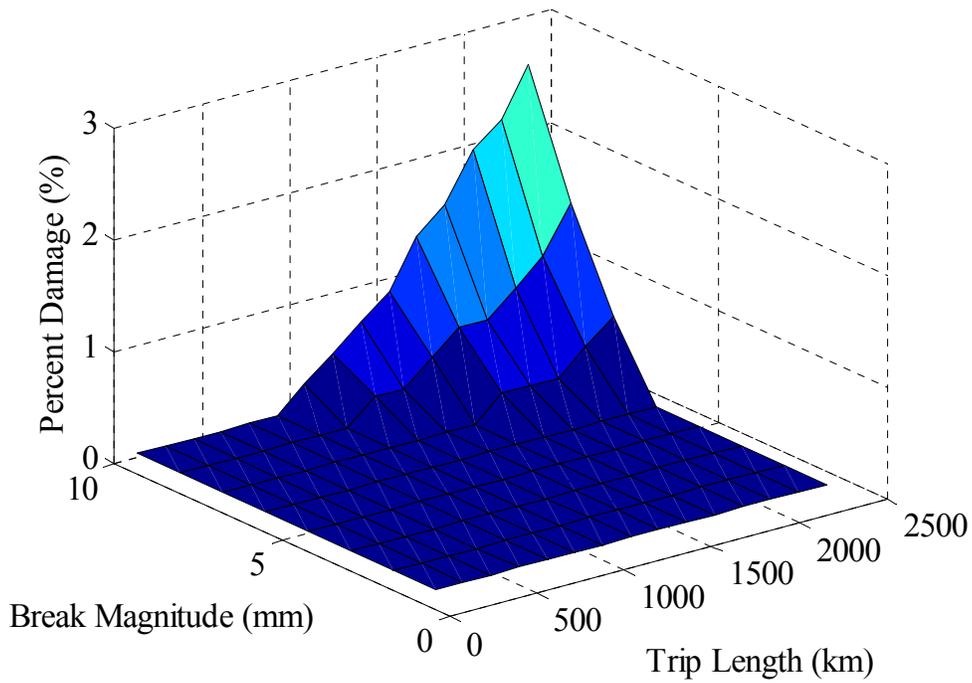


(b) 100% of slabs are faulted

Figure 8 – Damage induced by different fault magnitude and trip length



(a) One break per 1.6 km



(b) three breaks per 1.6 km

Figure 9 – Damage induced by different break magnitudes and trip length

5. Conclusions and Recommendations

In this paper, we propose a novel approach to estimate the damage induced to transported goods by roughness features. The proposed approach uses a mechanistic-empirical method to conduct product fragility assessment using numerical modeling of vehicle and product vibration response. A half-truck model was used to simulate vehicle vibrations. The principle of conservation of momentum (inelastic shocks) was used to estimate damage to goods. The analysis of three case studies for horticultural produce showed that:

- Air suspensions cause less damage to the transported goods than steel suspensions
- Shorter spacing between faults in jointed concrete pavements will cause less damage to the transported goods in trucks with steel suspension.
- Low speed will cause more damage to transported goods in trucks with steel suspensions than higher speed.
- More breaks on the road will cause more damage to the transported goods.

The approach reported in this paper could help in better estimating vehicle operating costs at the project and network levels. For routine application, a highway agency would need to run a given profile (for a given project) through the program developed in this study.

6. References

- Huang, Y. H. (2003), *Pavement Analysis and Design*, Prentice Hall.
- Zaabar, I. and K. Chatti, "Identification of Localized Roughness Features and Their Impact on Truck Durability", 11th International Symposium on Heavy Vehicle Weights and Dimensions, Melbourne, Australia, 14-17 March 2010.
- Chatti, K., Zaabar, I., and Lee, H.S. (2008), "Development of a simple diagnosis tool for detecting localized roughness features" in *Proceeding of the 9th International Conference on Concrete Pavements*, 673-689.
- Jones, C.S., Holt, J.E., Schoorl, D., "A model to predict damage to horticultural produce during transport", *Journal of Agriculture Engineering Research*, Vol 50, 1991, pp. 259–272.
- Rich, P., Van Pelt, T., Enshayan, K., and Cook, E., "Food Duel and Freeways: An Iowa Perspective on How Far Food Travels, Fuel Usage and Greenhouse Gas Emissions," June 2001:1. Leopold Center for Sustainable Agriculture, 27 February 2008
<http://www.leopold.iastate.edu/pubs/staff/ppp/food_mil.pdf>.
- Texas Department of Agriculture. Texas Agriculture Packs a Punch. Texas Agriculture Facts, Go Texan Program. 12 July 2007
http://www.gotexan.org/gt/channel/render/items/0,1218,1670_1693_0_0,00.html.
- Chesson, J.H., O'Brien, M., "Analysis of mechanical vibration of fruit during transportation". *Trans. ASAE*, Paper No. 69-628, 1971.
- Timm, E.J., Bollen, A.F., Dela Rue, B.T., Woodhead, I.M., "Apple damage and compressive forces in bulk bins during orchard transport", *Applied Engineering Agriculture*, Vol 14, 1998, pp.165–172.
- Hendrickson, John, "Energy Use in the U.S. Food System: A Summary of Existing Research and Analysis," 2004: 8. University of Wisconsin-Madison, College of Agricultural and Life Sciences, 27 February 2008
<http://www.cias.wisc.edu/pdf/energyuse2.pdf>.
- Cebon, D. (1999), *Handbook of Vehicle-Road Interaction*, Swets & Zeitlinger, Lisse, Netherlands.

- Hardy M.S.A. and Cebon D. (1995), “An investigation of anti-lock braking strategies for heavy goods vehicles”, Journal of Automobile Engineering, Institute of Mechanical Engineers, 209(D4), 263-271.